IXPE
Imaging
X-Ray
Polarimetry
Explorer

The Imaging X-ray Polarimetry Explorer (IXPE)

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on behalf of the IXPE Science Team
NASA/MSFC (Emeritus)

Presentation to the APS, April 2023

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The IXPE Team

Marshall Space Flight Center

PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving

Detector system funding, ground station

Spacecraft, payload structure, payload, observatory I&T

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Polarization-sensitive imaging detector systems

LASP Mission operations

Scientific theory

Thermal shields

Co-Investigator

Science Advisory Team

SAT currently comprises > 175 scientists from 13 countries

IXPE
Imaging
X-Ray
Polarimetry
Explorer

Launch 1:00 AM December 9, 2021

Equatorial Orbit
600 km altitude

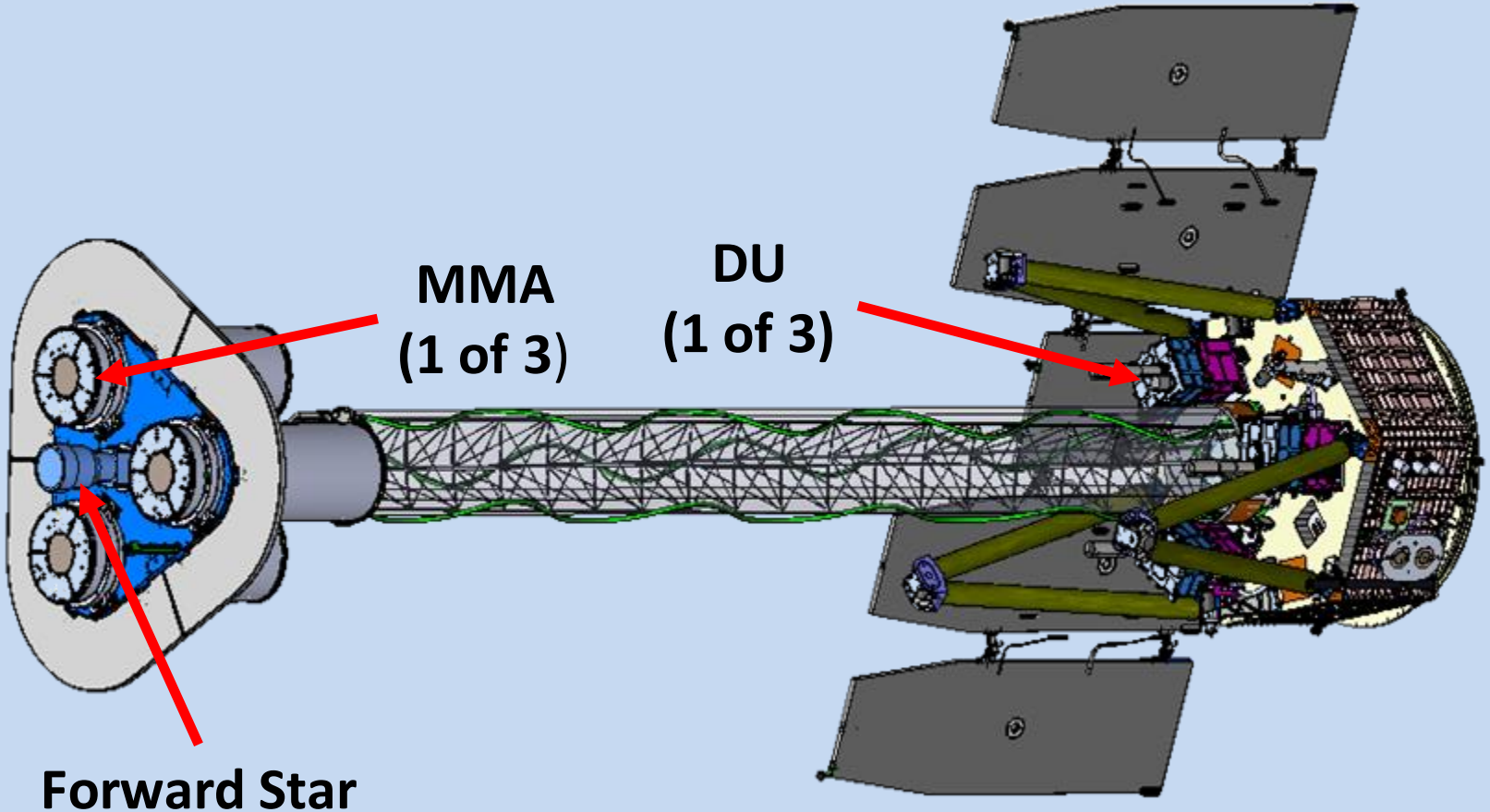
IXPE Imaging X-Ray Polarimetry Explorer

IXPE Mission Description

- Launched 2021 December 9, on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, optional extension with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA's HEASARC
  - During the first 3 months of the mission, including orbital checkout, all IXPE data shall be made publicly available at the HEASARC within 30 days of the end of an observation.
  - After the first 3 months of the mission, data shall be made available to the HEASARC within 1 week of the end of an observation

IXPE Imaging X-Ray Polarimetry Explorer

IXPE Deployed



5.2 m total length
4.0 m focal length

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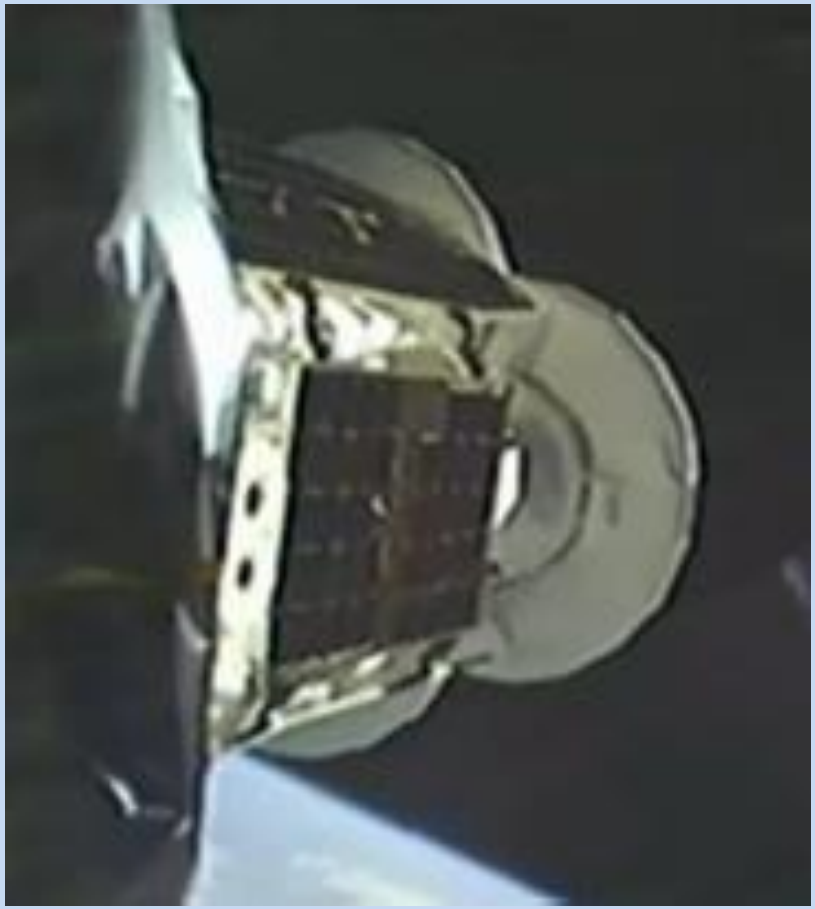
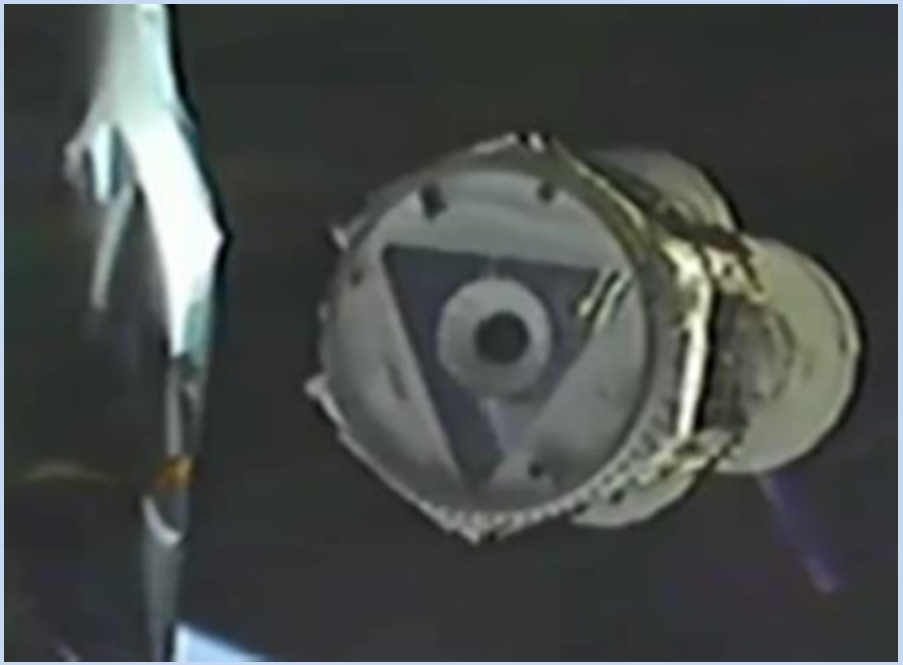
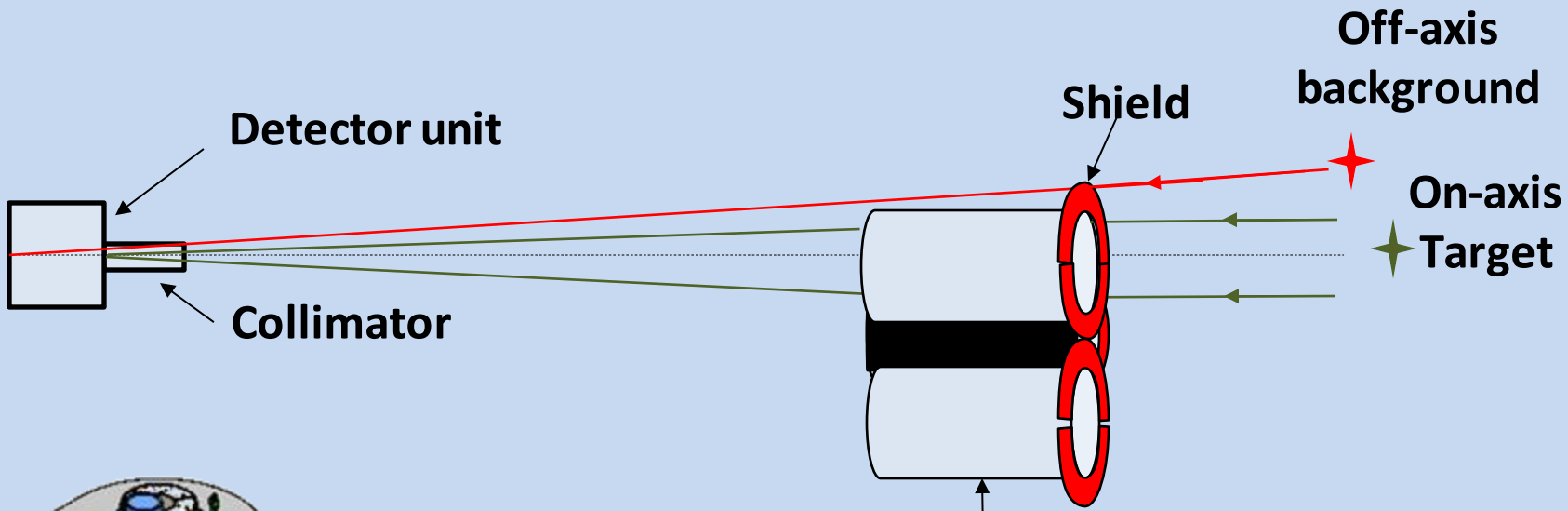
Release from the Falcon 9





Shield and Collimator Suppress Background

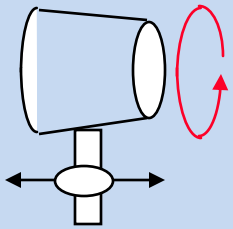


X-ray
Shield

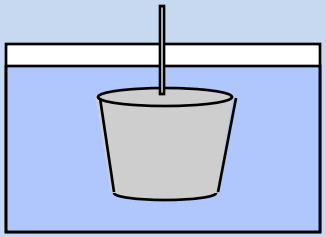
Optics Production

Mandrel fabrication

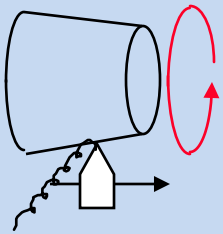
1. **Machine mandrel from aluminum bar**



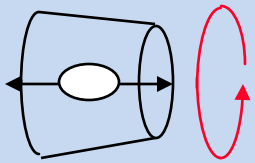
2. **Coat mandrel with electroless nickel (Ni-P)**



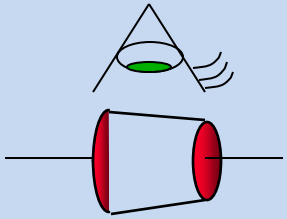
3. **Diamond turn mandrel to sub-micron figure accuracy**



4. **Polish mandrel to 0.3-0.4 nm RMS**

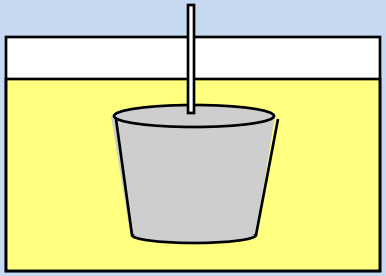


5. **Conduct metrology on the mandrel**

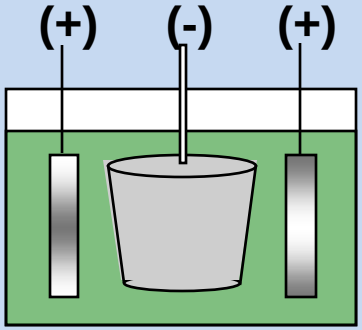


Mirror-shell forming

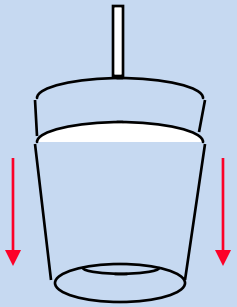
6. **Passivate mandrel surface to reduce shell adhesion**



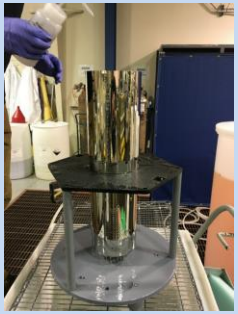
7. **Electroform Nickel/Cobalt shell onto mandrel**



8. **Separate shell from mandrel in chilled water**



Ni/Co electroformed IXPE mirror shell



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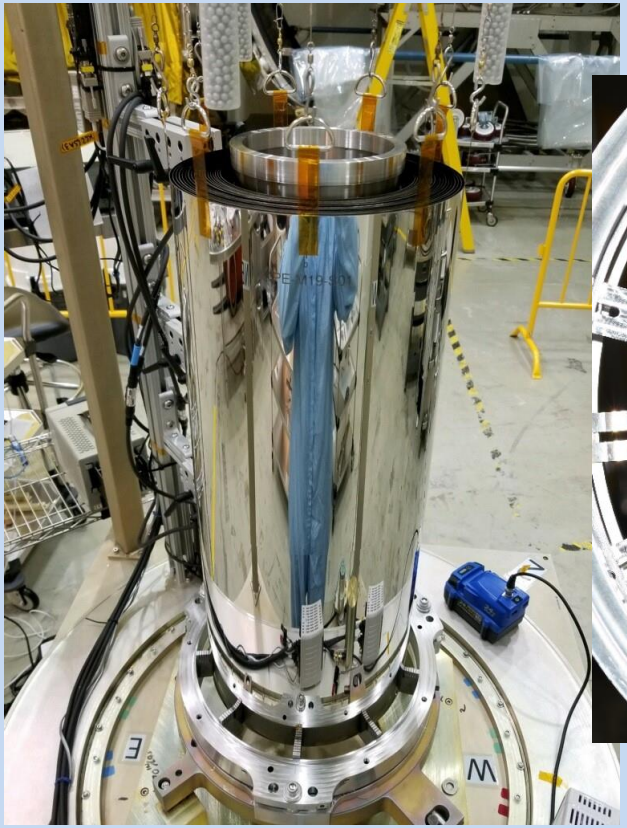
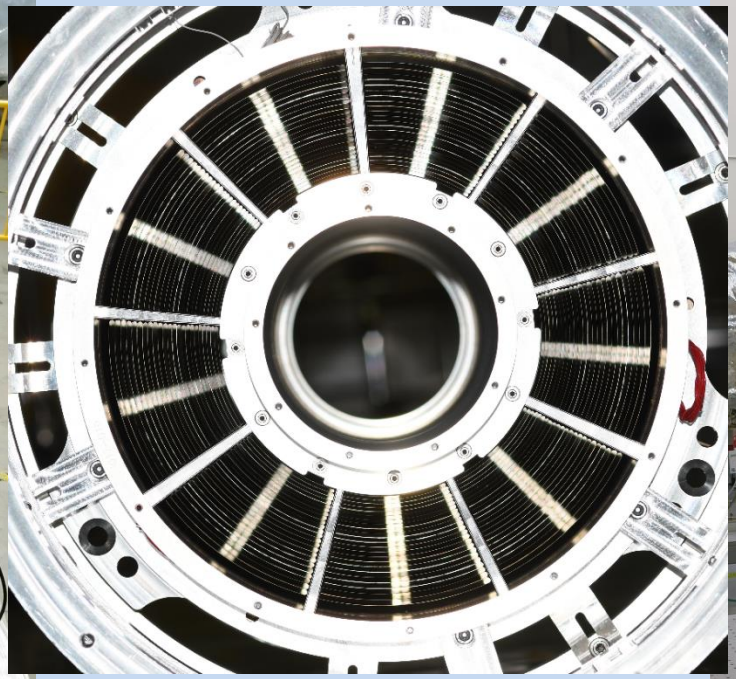
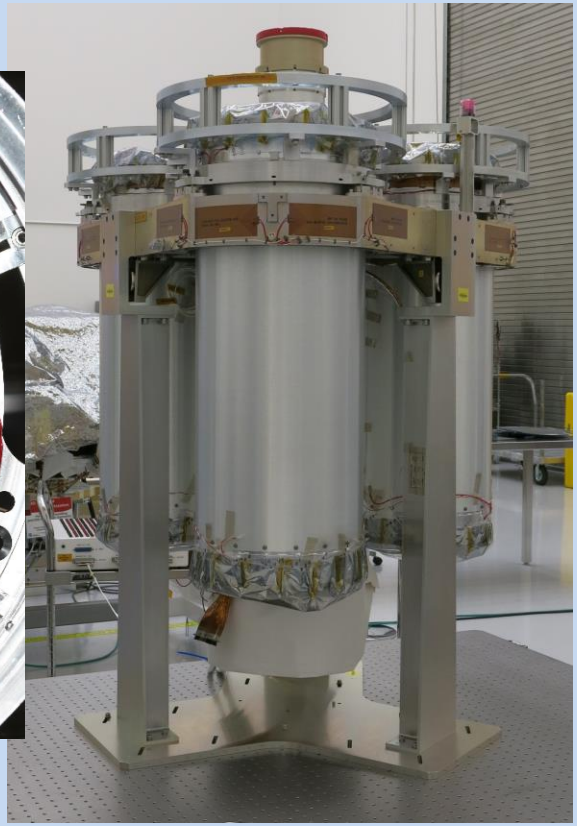
The Optics

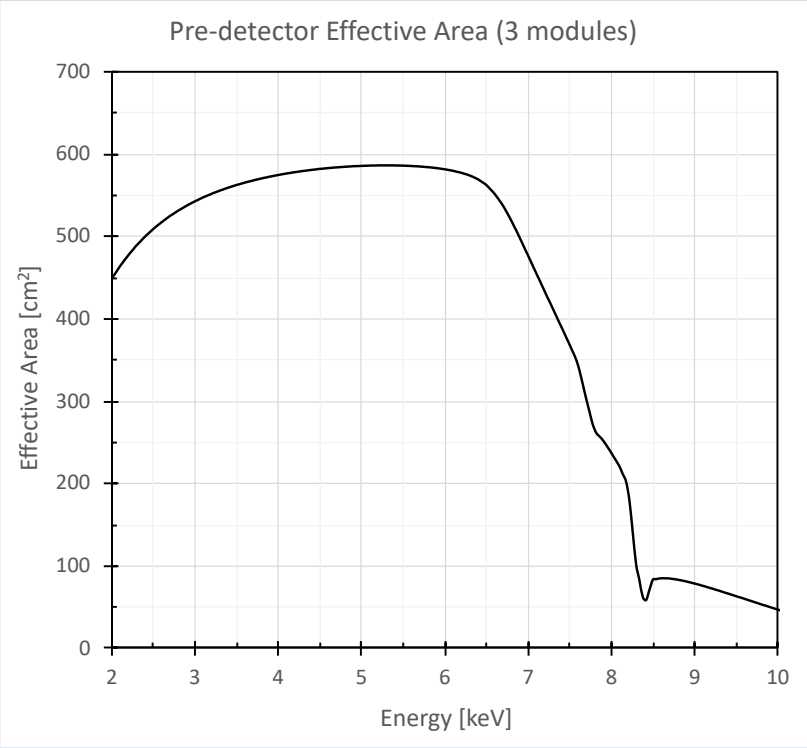






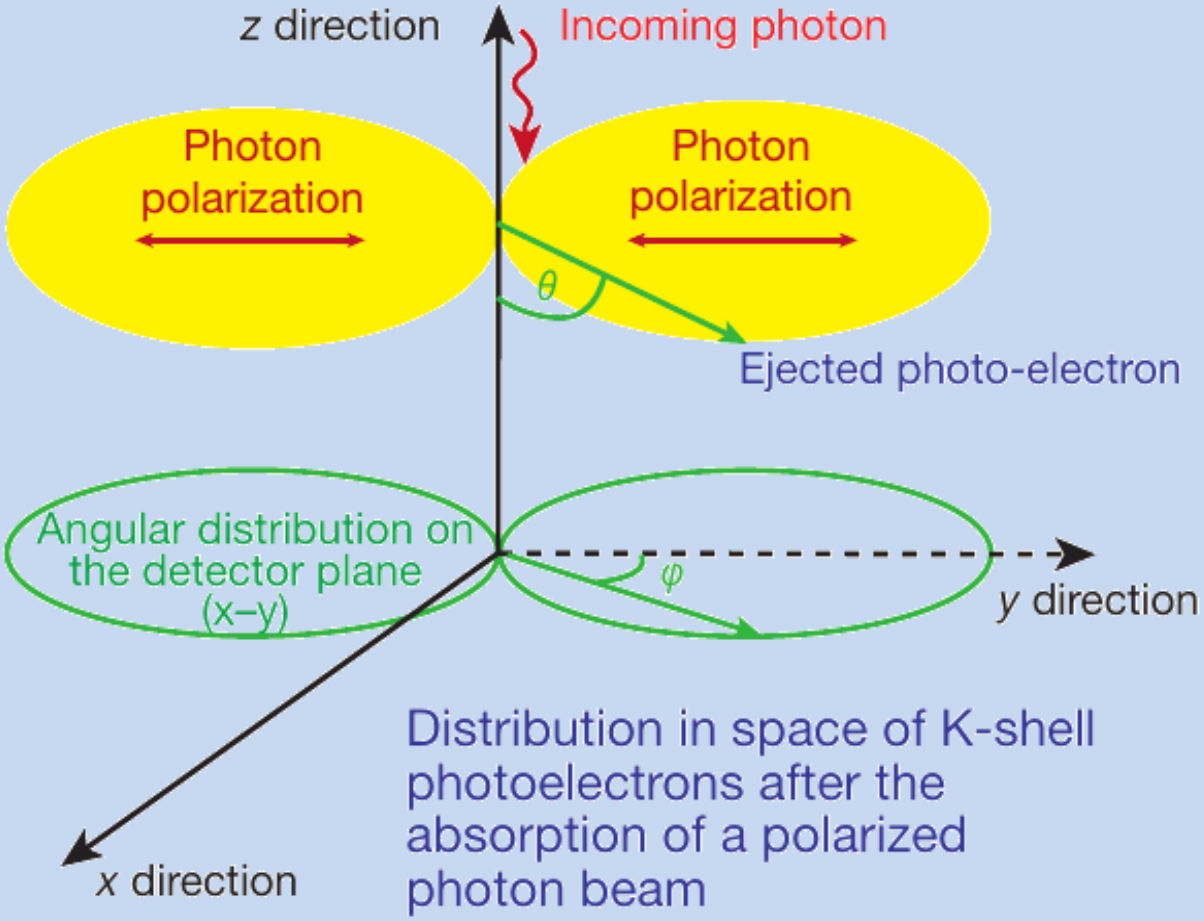
Mirror Module Assembly Properties

Property	Value
Number of modules	3
Mirror shells per module	24
Inner, outer shell diameter	162, 272 mm
Total shell length	600 mm
Inner, outer shell thickness	180, 250 µm
Shell material	Nickel cobalt alloy
Effective area per module	163 cm^2 (2.3 keV) ~ 192 cm^2 (3-6 keV)
Angular resolution	≤ 27 arcsec HPD
Detector limited FOV	12.9 arcmin
Focal length	4 m
Mass (3 assemblies)	93.12 kg

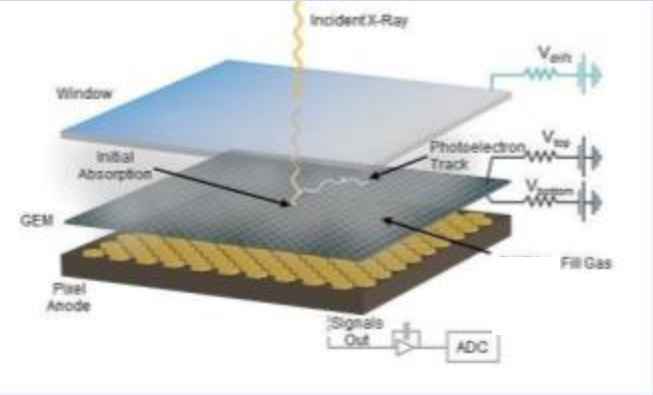


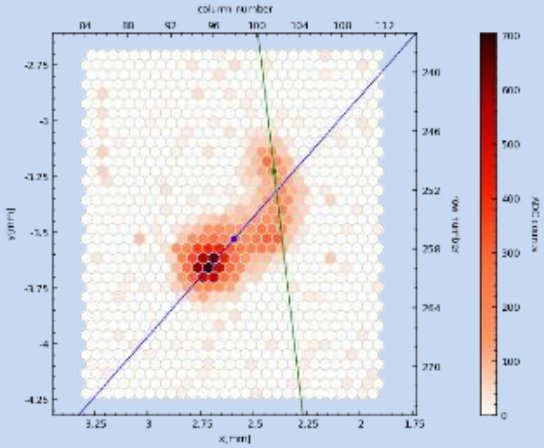
Polarization Detection Principle

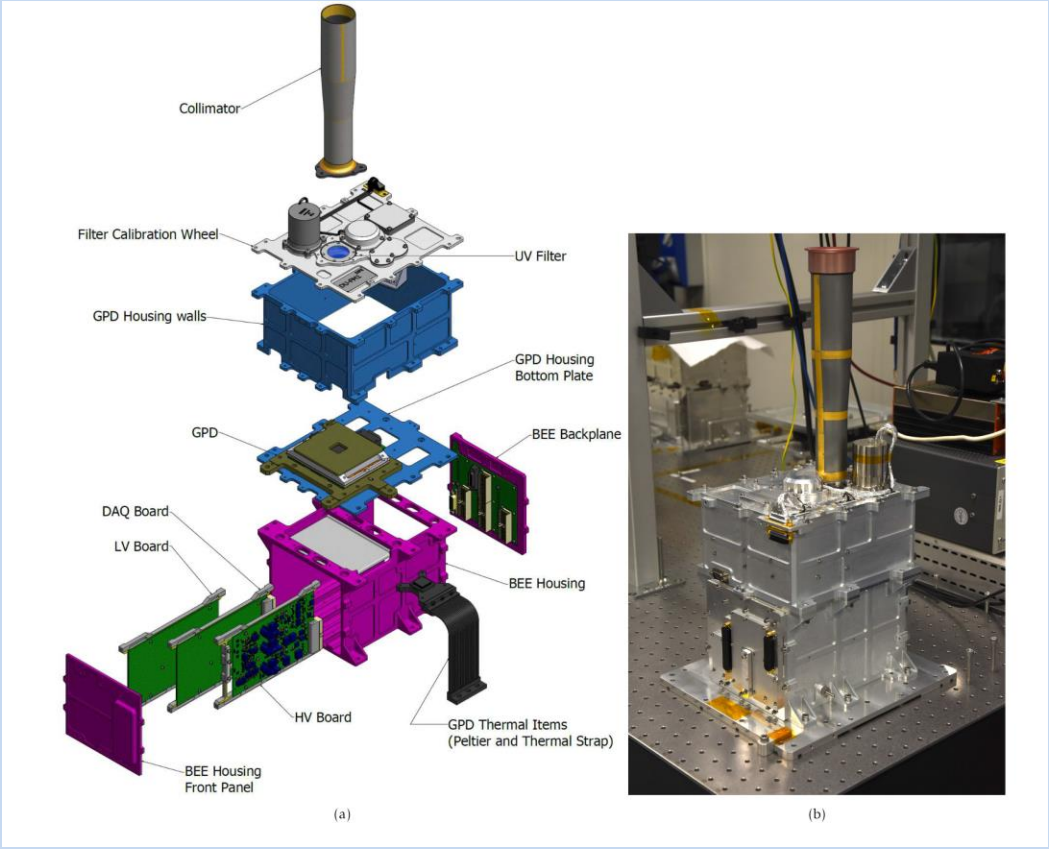
- **The detection principle is based on the photoelectric effect**



The Polarization-Sensitive Detectors





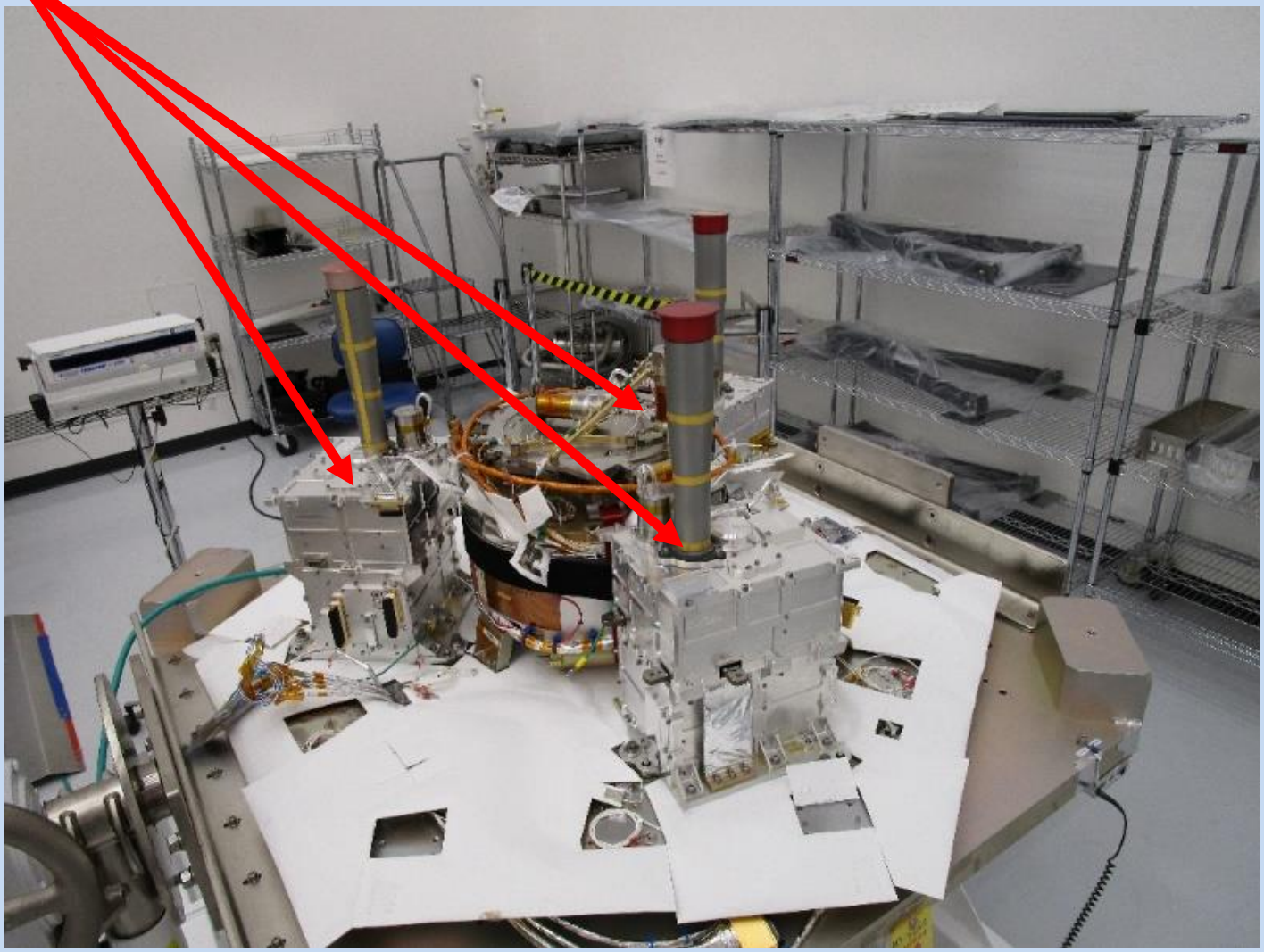


The distribution of the photoelectron initial directions determines the degree of polarization and the position angle

$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi\,, \text{ where } \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$

The Detectors

- The Detector Units (DUs) mounted to the spacecraft top deck at Ball



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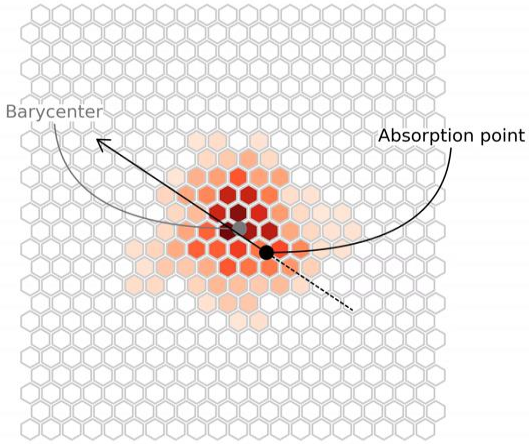
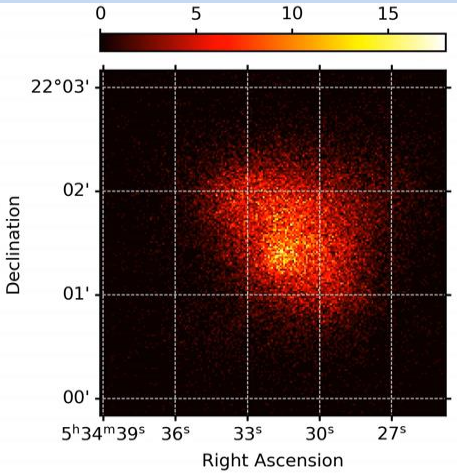
Detector Properties

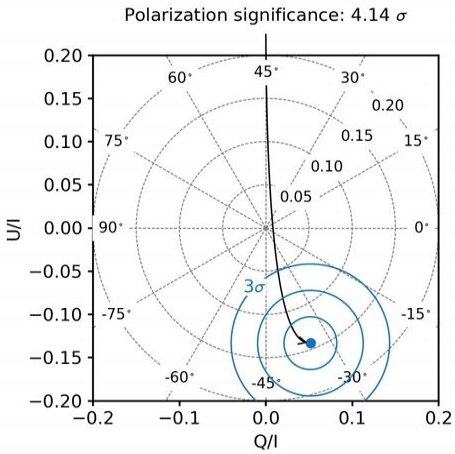
Parameter	Value
Sensitive area	15 mm × 15 mm (13 x 13 arcmin)
Fill gas and composition	DME @ 0.8 atmosphere
Detector window	50-µm thick beryllium
Absorption and drift region depth	10 mm
GEM (gas electron multiplier)	copper-plated 50-µm liquid-crystal polymer
GEM hole pitch	50 µm triangular lattice
ASIC pixelated anode	Hexagonal @ 50-µm pitch
Number ASIC readout pixels	300 × 352
Spatial resolution (FWHM)	≤ 123 µm (6.4 arcsec) @ 2 keV
Energy resolution (FWHM)	0.57 keV @ 2 keV ($\propto \sqrt{E}$)
Useful energy range	2 - 8 keV

How it Works: Observing the Crab Nebula

Replay of a sample of events obtained by one of IXPE's three detectors
(39 ks livetime, segment 1 of 2 of the Crab nebula observation)

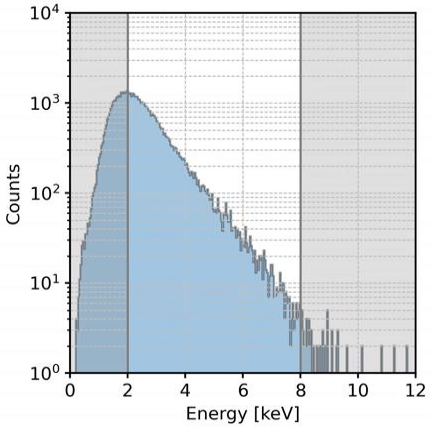






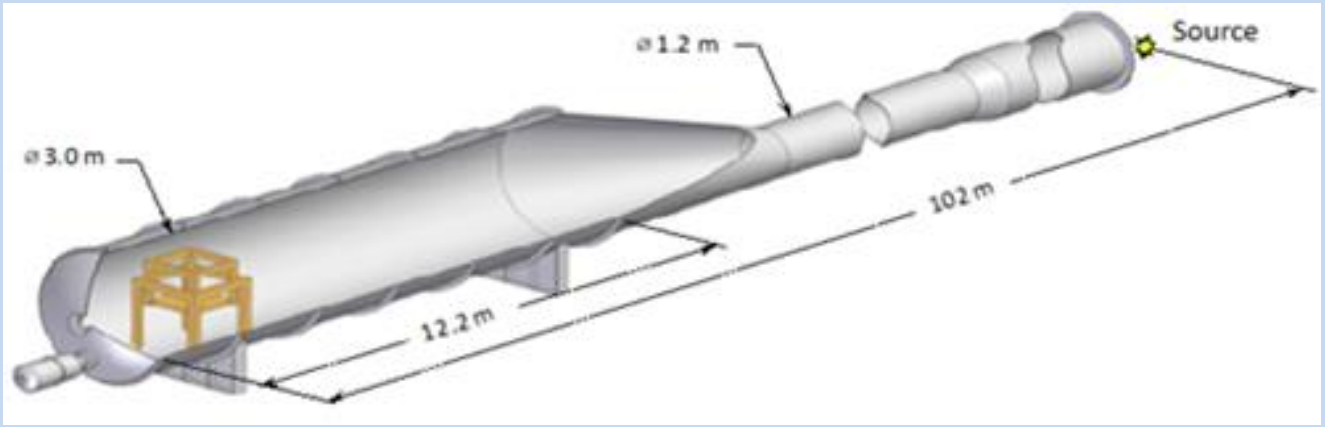
Target Name
Crab (obs. 01001099)
Observation Start
2022-02-21T16:35:33.184
Observation End
2022-03-08T02:17:56.184
Detector Unit
DU1 (DU_FM2)

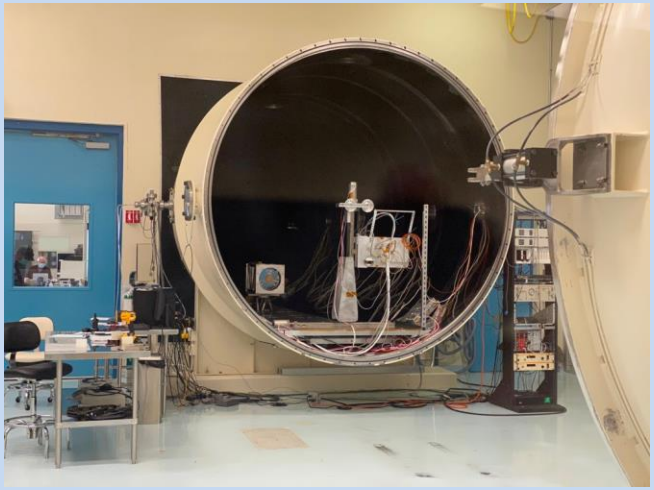
Accumulated statistics in 2.0-8.0 keV
40201 events
Mission elapsed time
162237408.245864 s
Energy
2.42 keV
Sky position (R. A., Dec.)
(83.632, 22.026) decimal degrees
Stokes parameters (q, u)
(-1.7416, -0.7097)

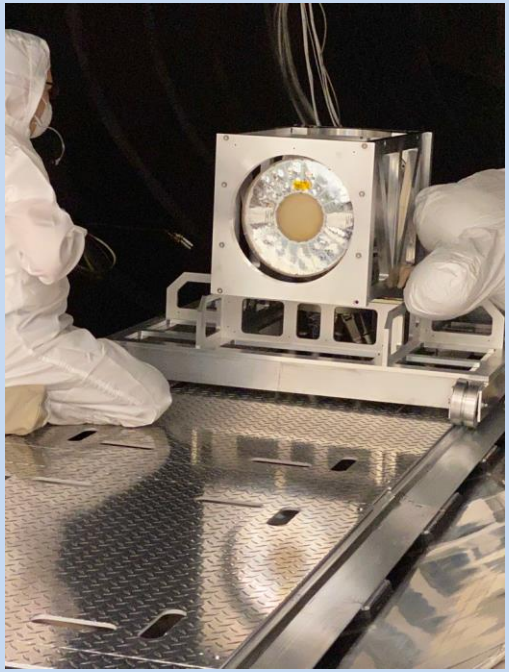


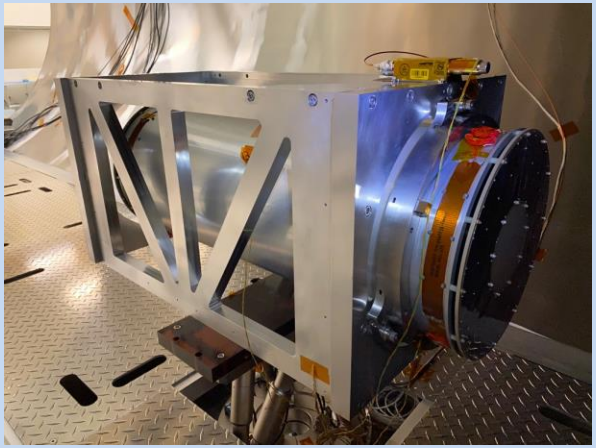
Powered by https://github.com/lucabaldini/ixpeobssim

Calibration: MSFC Stray Light Test Facility



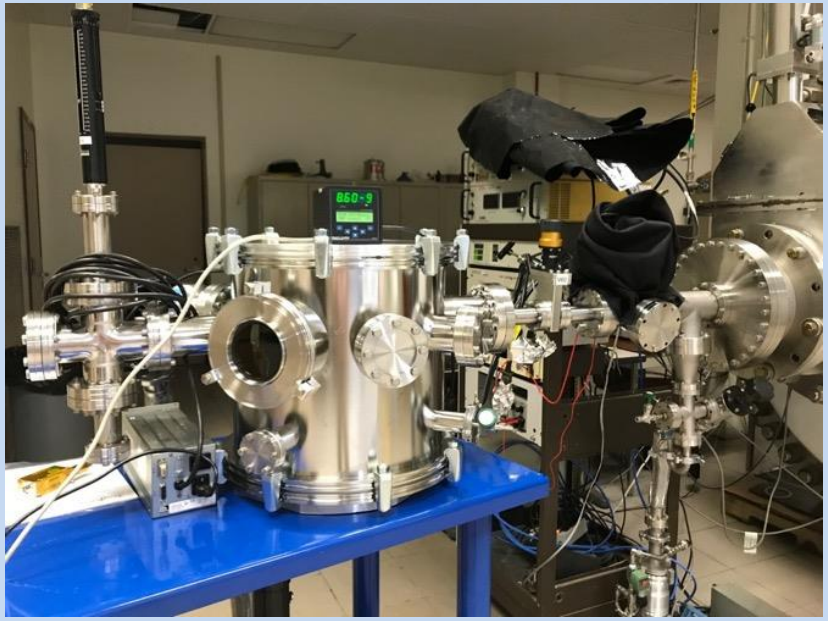


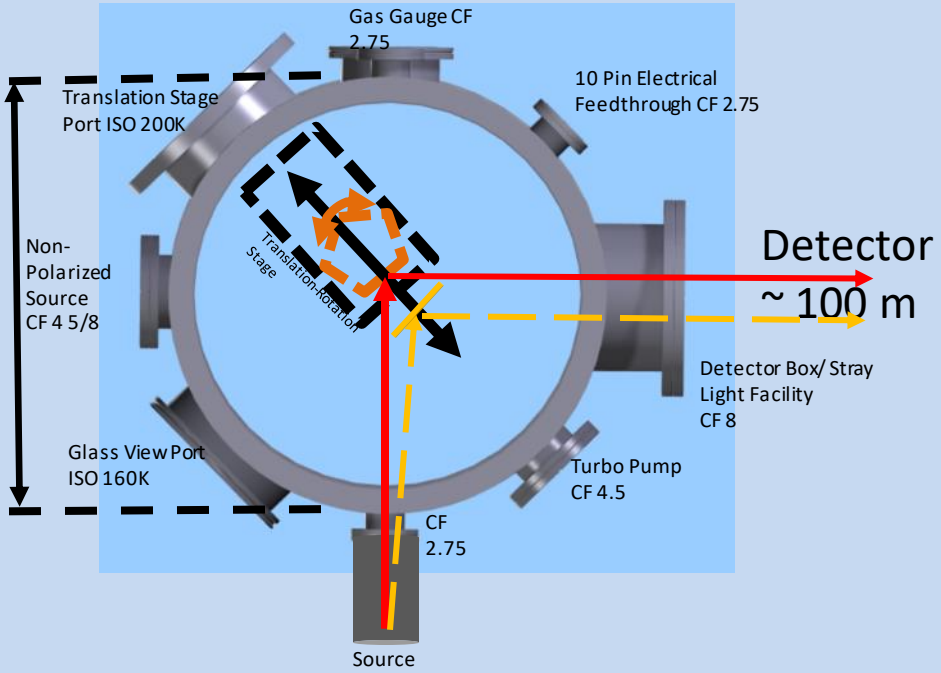




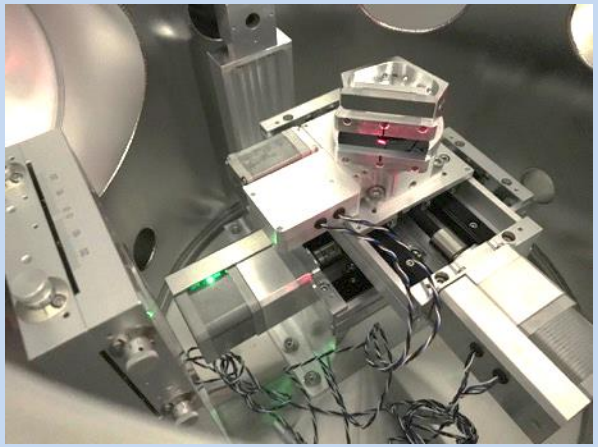
Polarized Sources

- **3 Polarized Sources**
  - **Crystal Box**
    - **Holds all X-ray sources**
    - **Holds crystals, which polarize source**





Energy	X-ray Tube	Crystal	Polarization
2.7 keV	Rh	Ge(111)	> 99%
4.5 keV	Ti	Si(220)	> 99%
6.4 keV	Fe	Si(400)	> 99%



Interior of Crystal Box, showing stages and crystal being aligned on turret

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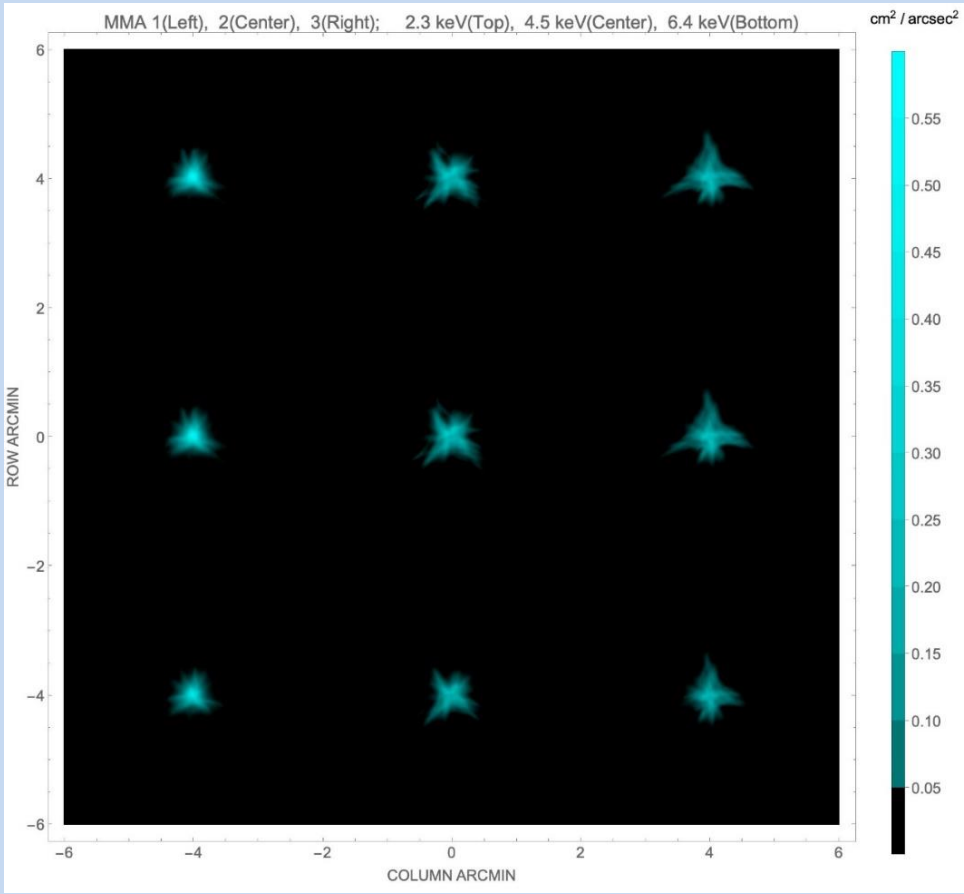
Angular Resolution

MMA	#1	#2	#3
6.4 keV	18.9″	24.8″	24.2″
4.5 keV	18.9″	25.0″	26.9″
2.3 keV	18.7″	24.5″	26.7″

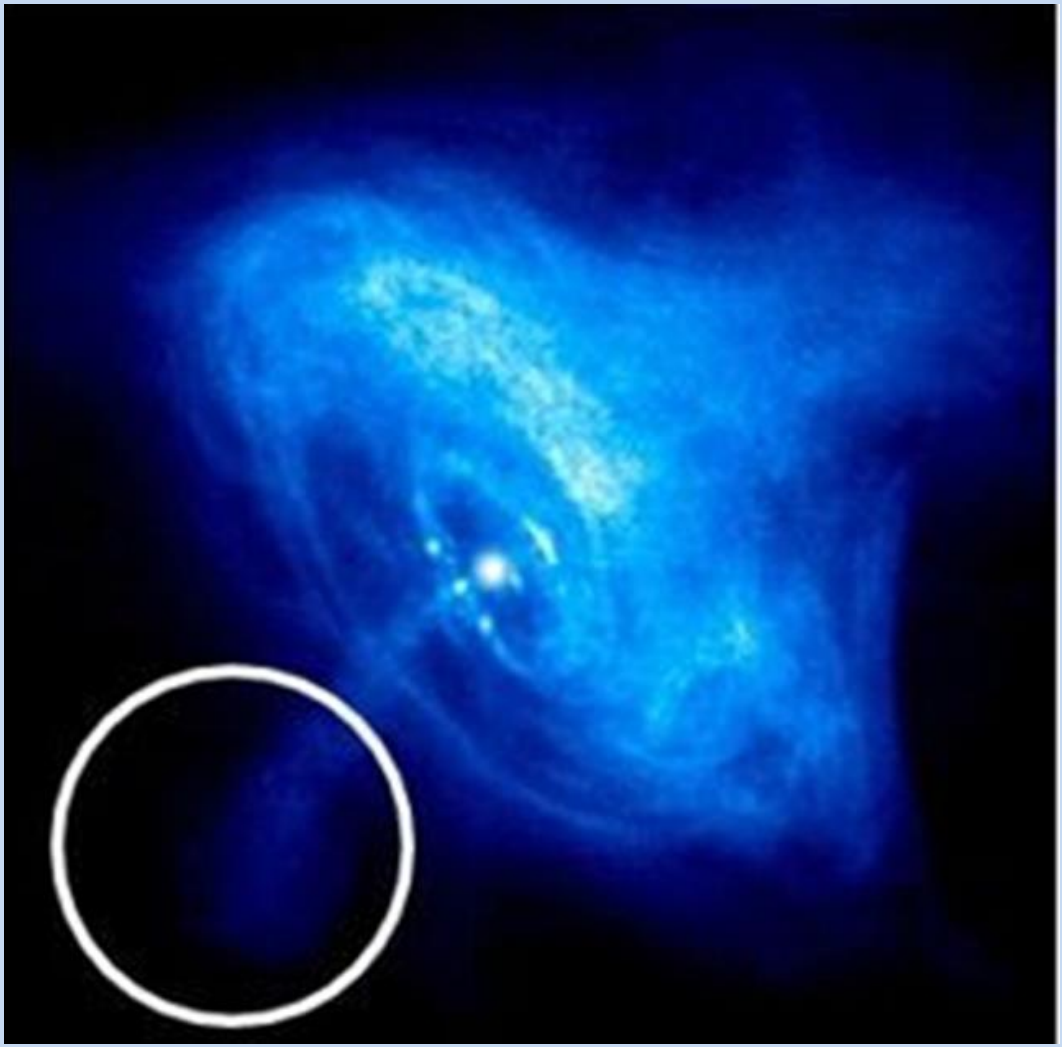
Values in the table are half-power diameters (HPDs) for the individual MMAs alone. These need to be adjusted for alignment errors, detector resolution, focus etc. to determine the on-orbit system-level resolution.



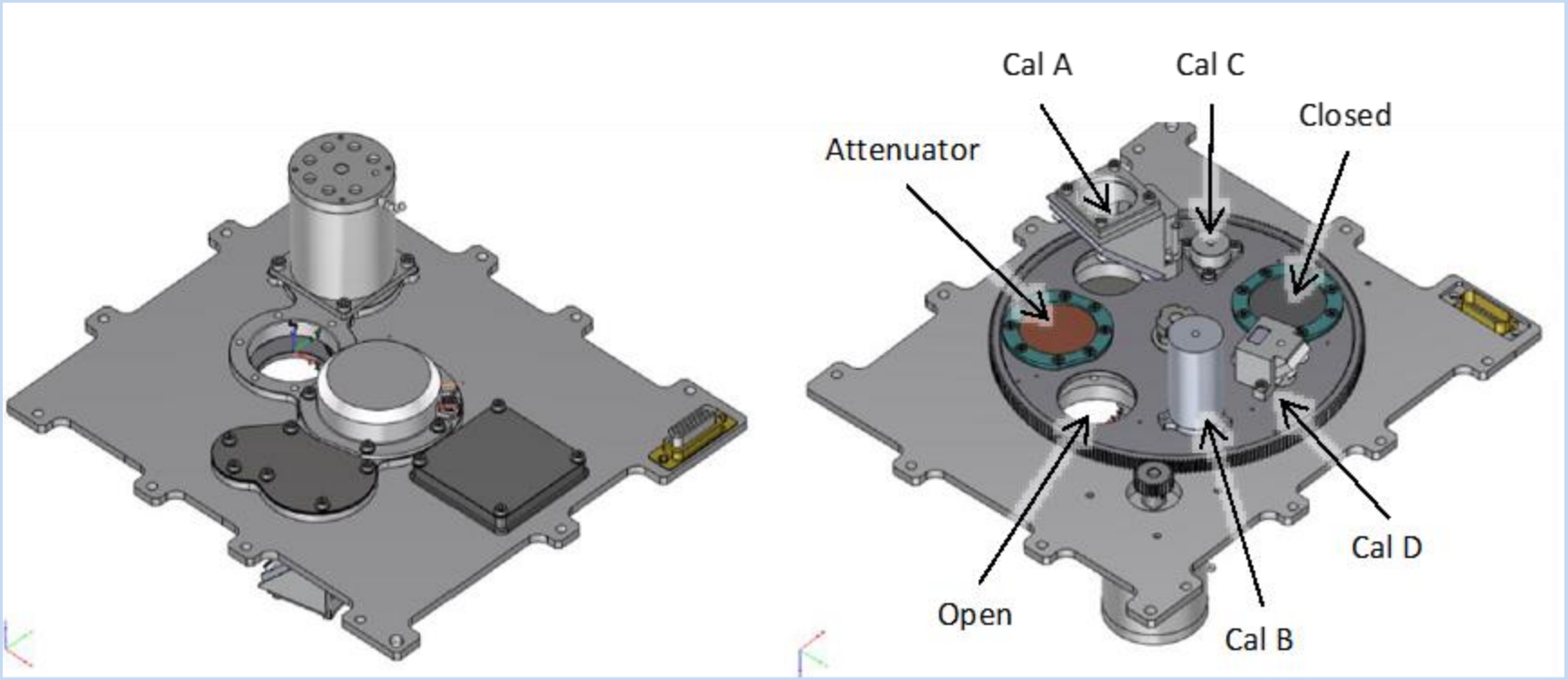
- Based upon X-ray calibration, analysis, and on-orbit images, the system-level performance is ≈ 30″ HPD

Imaging polarimetry

- **IXPE 30” half-power diameter on Chandra image**



Filter Calibration Wheel Assembly



Filter and Calibration Wheel (FCW), providing open, attenuator, and closed positions, plus four ^{55}Fe-powered calibration sources:

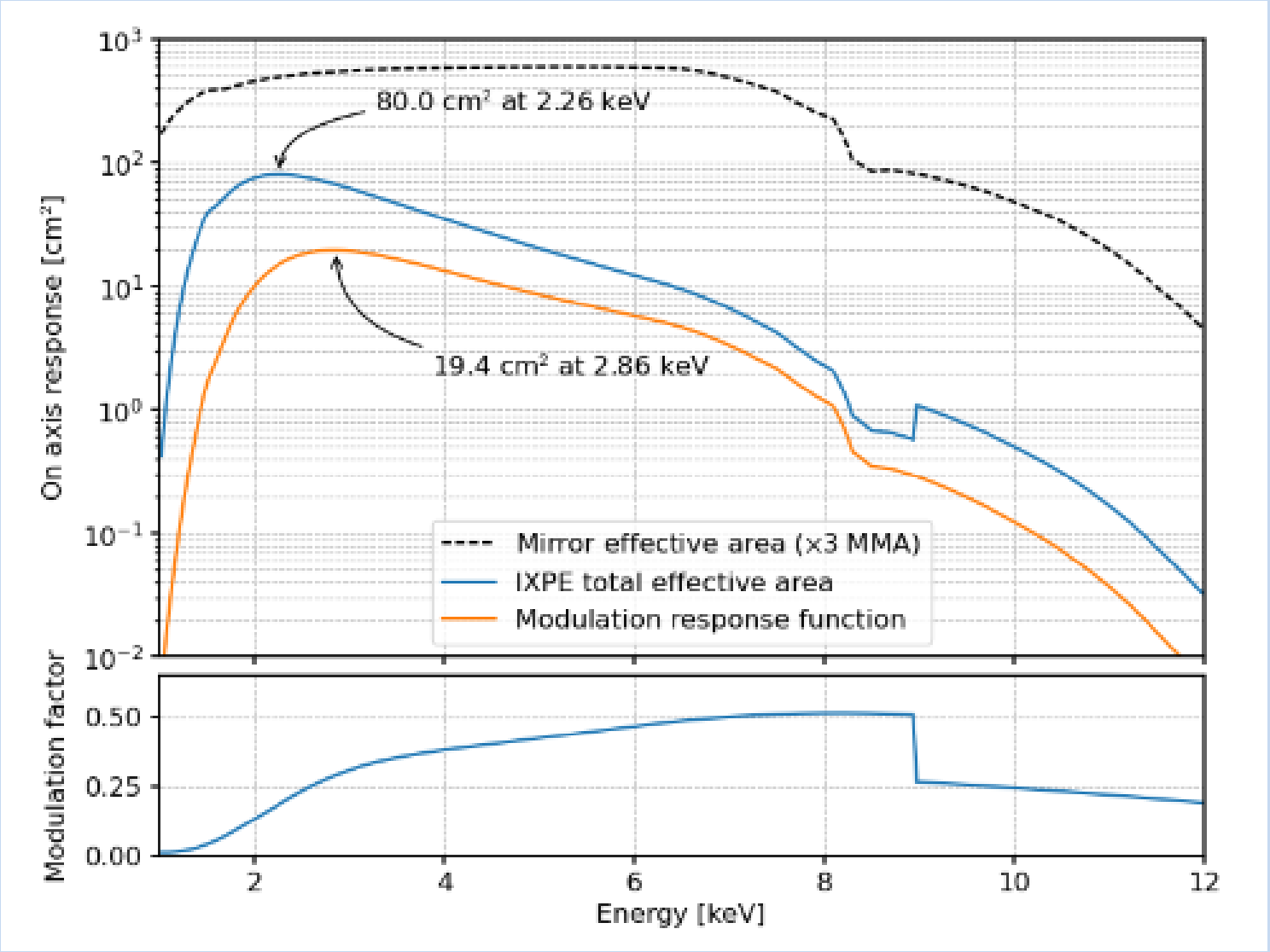
- **Cal A – Bragg-reflected polarized 2.98-keV (Ag-Lα fluorescence) and 5.89-keV (Mn-Kα)**
- **Cal B – unpolarized 5.89-keV spot**
- **Cal C – unpolarized 5.89-keV flood**
- **Cal D – unpolarized 1.74-keV (Si-Kα fluorescence) flood**

The Minimum Detectable Polarization (MDP)

$$MDP_{99}(\%) = (4.29x10^4 / M(\%))\sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}$$

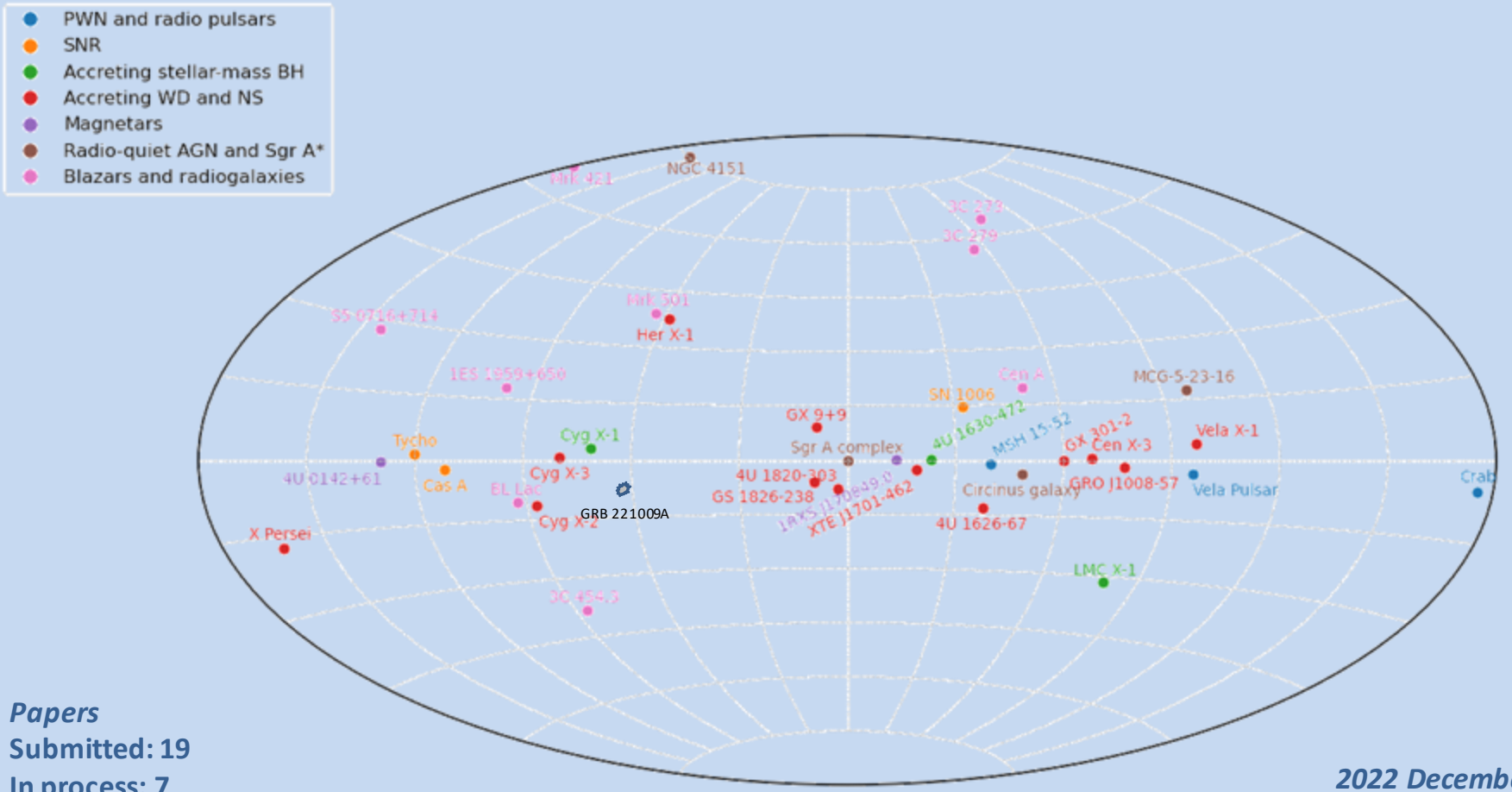
- R_S is the observed source counting rate
- R_B is the observed background counting rate
- t is the integration time
- M is the modulation factor, i.e. the amplitude of the variation of the ensemble of position angles for a 100% polarized source

Effective Area and Modulation Factor



The Targets

IXPE's first observations



Papers
Submitted: 19
In process: 7
Accepted/Published: 12
66 presentations at 14 international conferences

2022 December 8
Sources observed: 39
Polarization detected (> 99.99% confidence): 19

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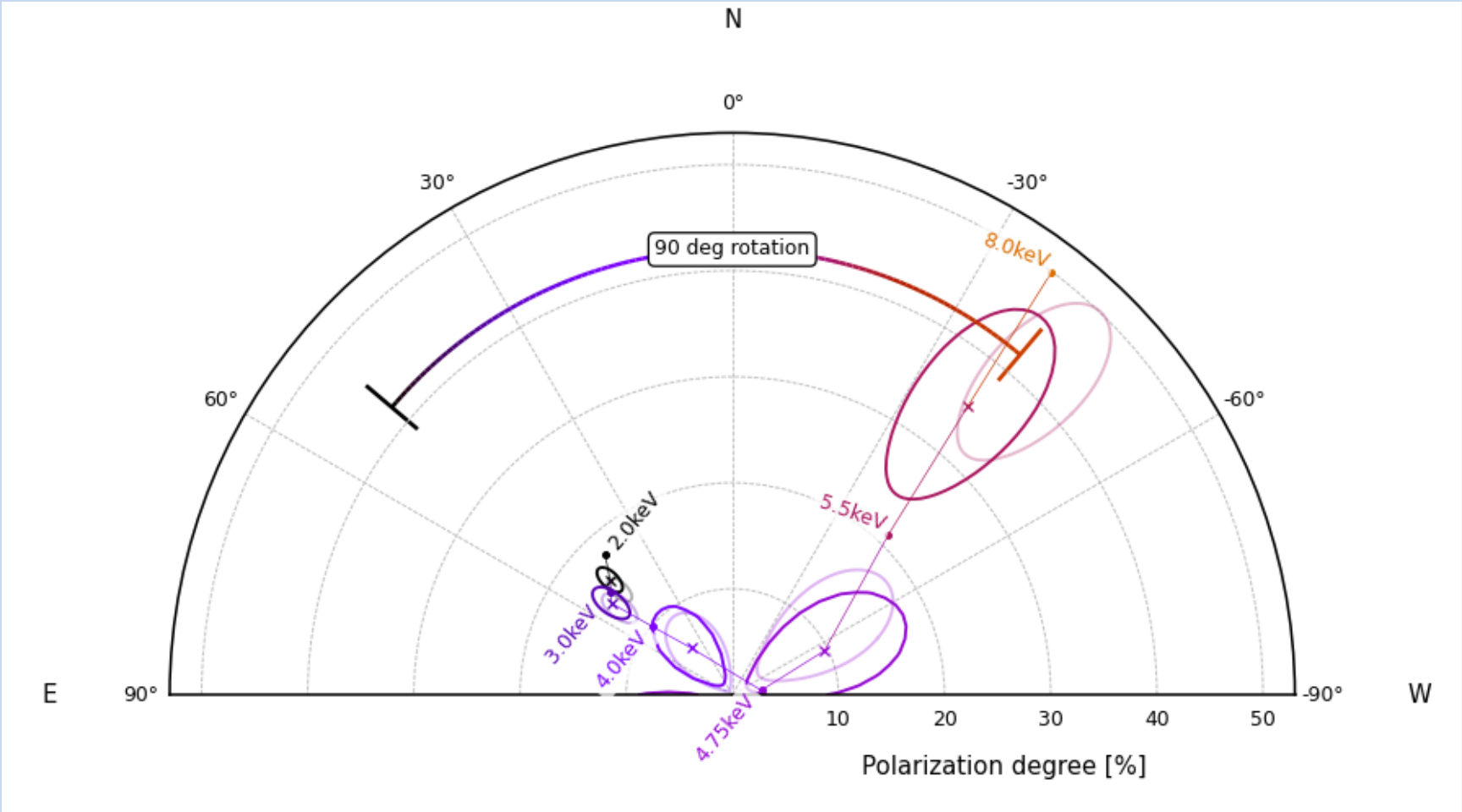
The Early Results

- **IXPE's first observations have been especially rewarding**
- **Many leading to unexpected results**
  - **See the following talks for details**
- **Here we present two snapshots**

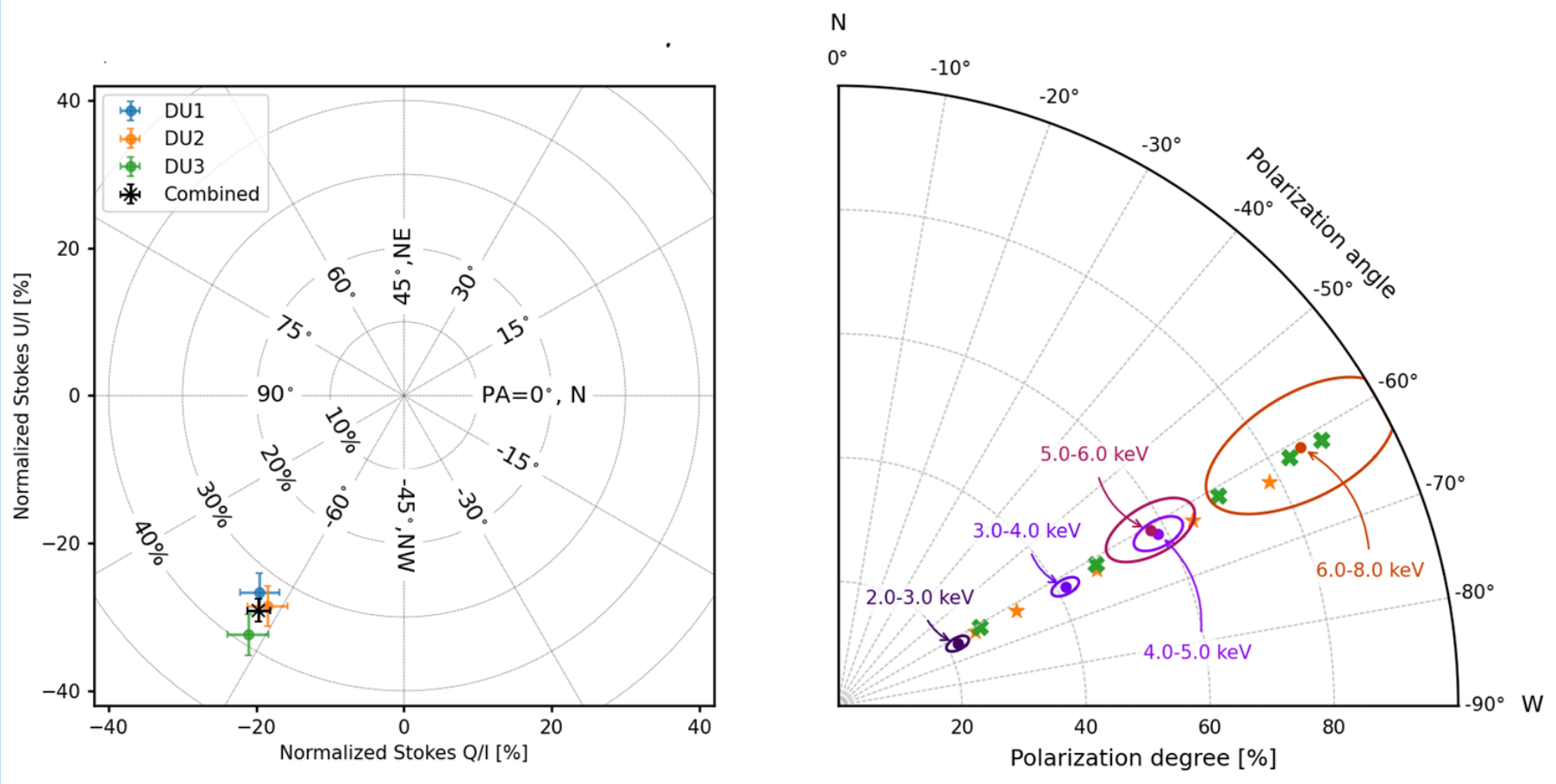
Magnetars (First and Brightest)

IXPE observations of the magnetar 4U0142 show evidence for birefringence where the position angle flips by 90°



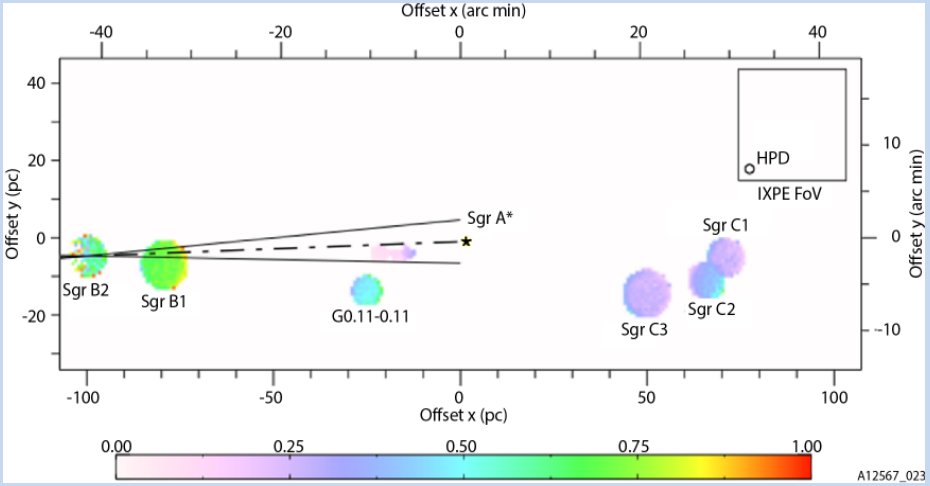
Another Magnetar (1RXS J1708)

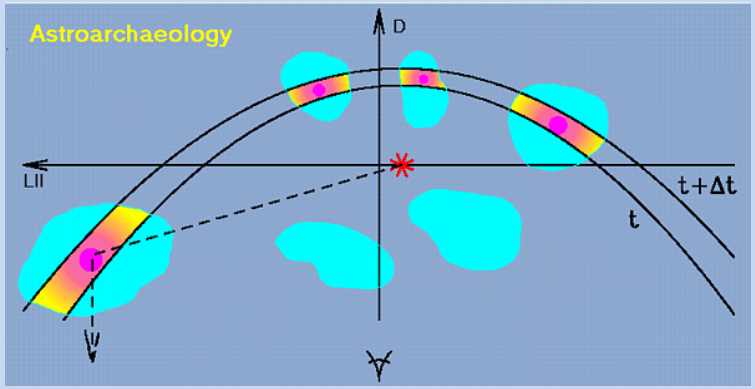
However, IXPE observations of the magnetar 1RXS J1708 show energy dependence but no position angle flip



Was Sgr A 10^6 × more active?*

- **Galactic Center molecular clouds (MC) are known X-ray sources**
  - **MCs reflect X-rays from Sgr A***
    - **X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A***





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A Hint